Test facility to study a Liquid Argon detector with Xenon Doping

AL&X

Argon Liquido & Xenon

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Grant Giovani CSN5 INFN - Concorso n. 23246/2021

1 Dicembre 2021

Introduction

Liquid argon (LAr) is widely used in particle physics experiments (e.g., neutrino oscillations, neutrinoless $\beta\beta$ decay and dark matter)

LAr advantages

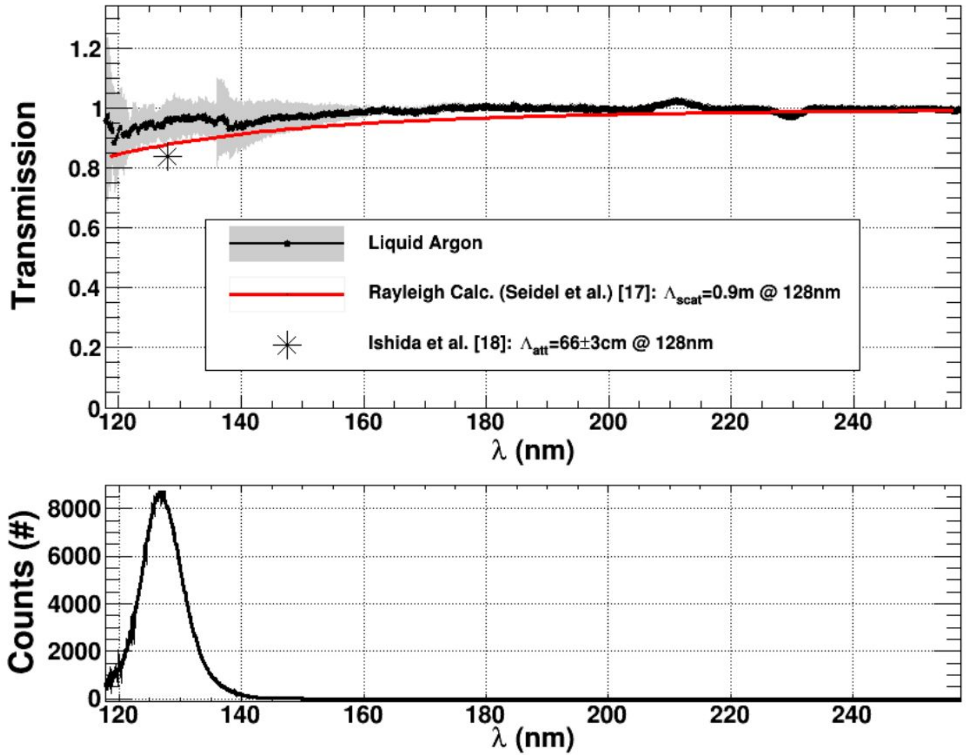
- **high light yield** of 40 γ/keV (energy resolution ~ 1% at 1 MeV)
- **low cost** of ~ 5 €/kg
- **excellent discrimination** of ionizing particles, thanks to different decay time of singlet (7 ns) and triplet (1.3 μs) scintillation component

LAr challenges

- vacuum ultraviolet (VUV) **light scintillation** peaked at 128 nm, ⇨ **difficult to detect**
- **long triplet decay time** of 1.3 μs, ⇨ **large dead time**
- short **attenuation length** (~ 1 m), ⇨ **limit detector size**

Adding a little amount of Xe may improve LAr properties, research groups started to explore this innovative approach for future applications

State of Art: LAr attenuation length



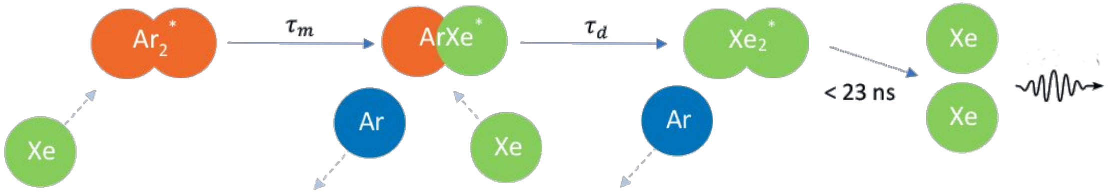
λ_{LAr} is a crucial parameter to study the LAr scintillation light

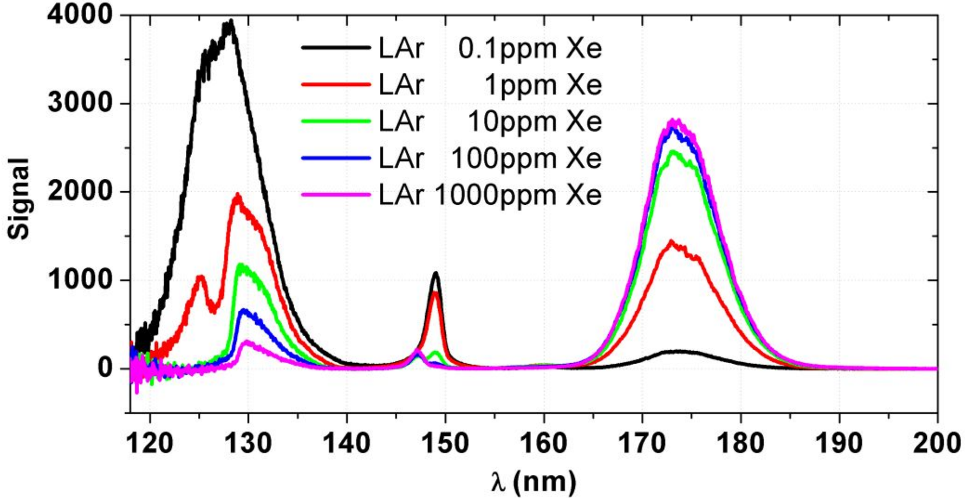
- controversial measurements reported by previous works
- Neumeier et al. published **λ_{LAr}>1.1 m**, larger than other results in literature
- impurities lead to **strong absorption features** (including Xe at ppm level)

2015 EPL **111** 12001

State of Art: emission spectrum

Xe-doping in LAr produces energy transfer from Ar excimer to Xe atoms, scintillation light shift to Xe emission peaked at 175 nm

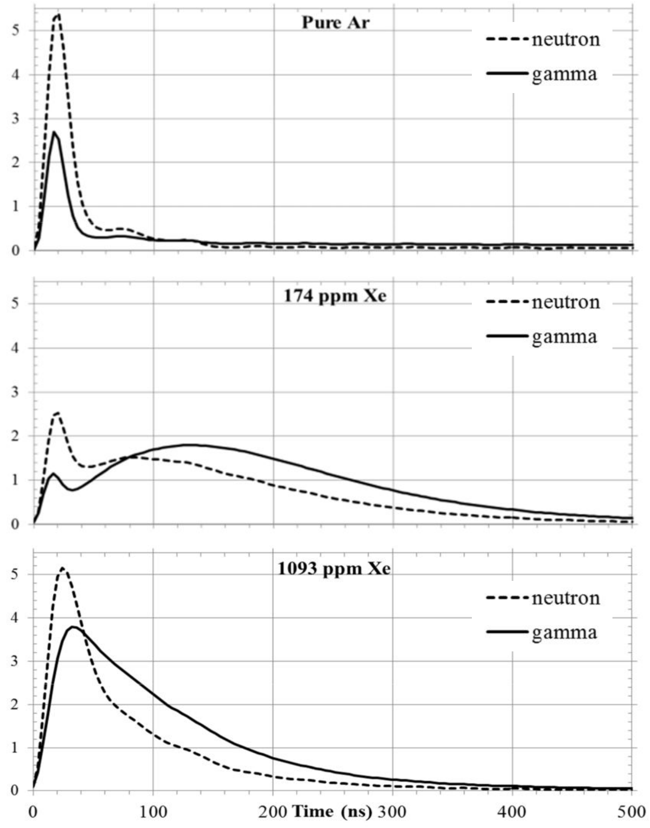




- spectrum modification **almost completed with 10 ppm of Xe**
- **heteromolecular excimer ArXe*** emission at 150 nm, observed with low Xe doping (< 10 ppm)

2015 EPL **109** 12001

State of Art: signal shape modification



- **in pure LAr** the signal has fast and slow components:

$$I_{LAr}(t) = A_s e^{-t/\tau_s} + A_f e^{-t/\tau_f}$$

- **with Xe-doping up to 300 ppm** additional term to describe energy transfer from Ar to Xe excimers (only slow component):

$$I_{LArXe}(t) = A_s e^{-t/\tau_s} + A_f e^{-t/\tau_f} - A_{ts} e^{-t/\tau_{ts}}$$

- **with Xe concentration > 300 ppm** emission of fast component is also observed, resulting in increased **pulse shape discrimination (PSD)** efficiency

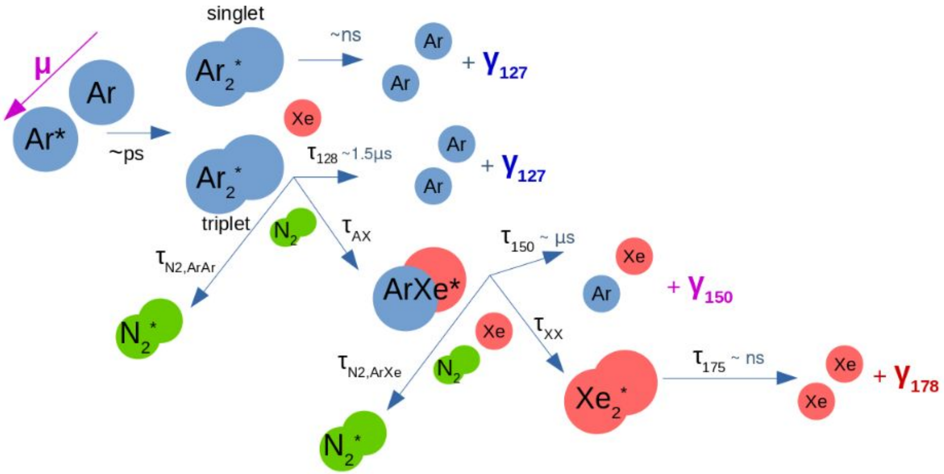
$$I_{LArXe}(t) = A_s e^{-t/\tau_s} + A_f e^{-t/\tau_f} - A_{ts} e^{-t/\tau_{ts}} - A_{tf} e^{-t/\tau_{tf}}$$

2014 JINST **9** P06013
2019 JINST **14** P09022

State of Art: light detection efficiency

Xe-doping leads to an increase of light detection efficiency

- **longer attenuation length** of 175 nm light in LAr (> 3 m) due to a longer Rayleigh scattering length
- **mitigation of possible light suppression** due to impurities (e.g., N_2, O_2)



arXiv:2109.05858
arXiv:2111.00347
NIMA **1011** 165575 2021

Goals and Expected Results

The AL&X project aims to study benefits and reliability of Xe-doped LAr for next generation physics experiments

LAr attenuation length

investigate on **ternary mixture** with LAr, Xe and other contaminants (e.g., N_2, O_2), **never performed by previous works**

Light detection efficiency

novel approach directly reading LAr scintillation light with VUV sensitive SiPMs; compare with standard solution

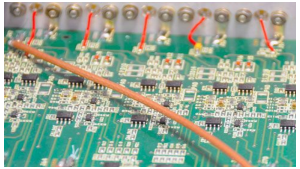
Signal shape and PSD

study of **re-mission of fast component** of LAr scintillation light, **divergent results available on this topic**

LAr light yield

Xe-doping mitigates light losses due to contaminants in LAr, **up to now it's not established the impact on pure LAr**

Experimental setup

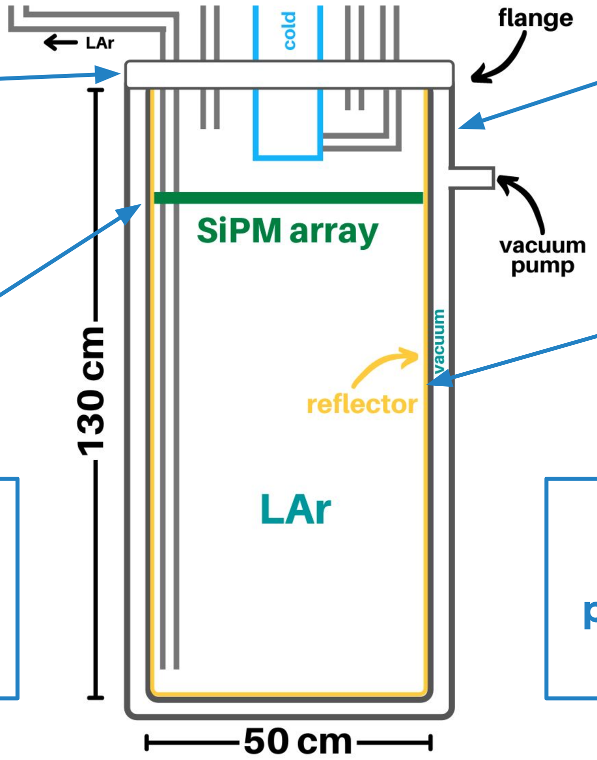

- the experimental site is the **INFN Laboratori Nazionali del Gran Sasso**, here the project can take advantage of existing infrastructures and expertise
- space required for the setup **4×4 m^2**
- **extremely high-purity setup** with components in stainless steel and **purification system**
- **simple and symmetric geometry** to allow efficient light collection and system simulation (GEANT4)

Experimental setup: LAr cryostat

top flange provides LAr inlet and outlet and connection to **cryogenics**

SiPM array to read-out scintillation light

system to insert **radioactive sources,** cosmic muons to study λ_{LAr} selected by **external scintillators**



stainless steel cryostat double wall chamber, **cylindrical symmetry**

reflectors to improve VUV light collection

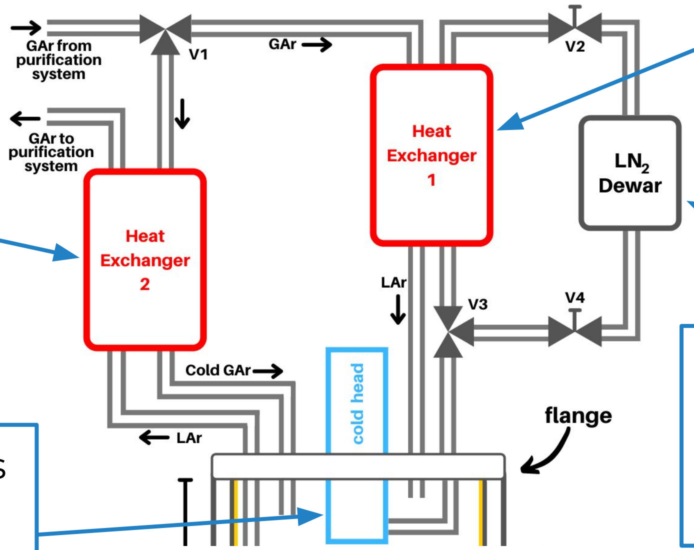
Precise size and geometry evaluated during design phase, also considering costs and construction times

Experimental setup: cryogenics system

The cryogenic system fills the cryostat with LAr and connects cryostat to the gas system

2nd Heat Exchanger for LAr purification w/o losing thermal efficiency

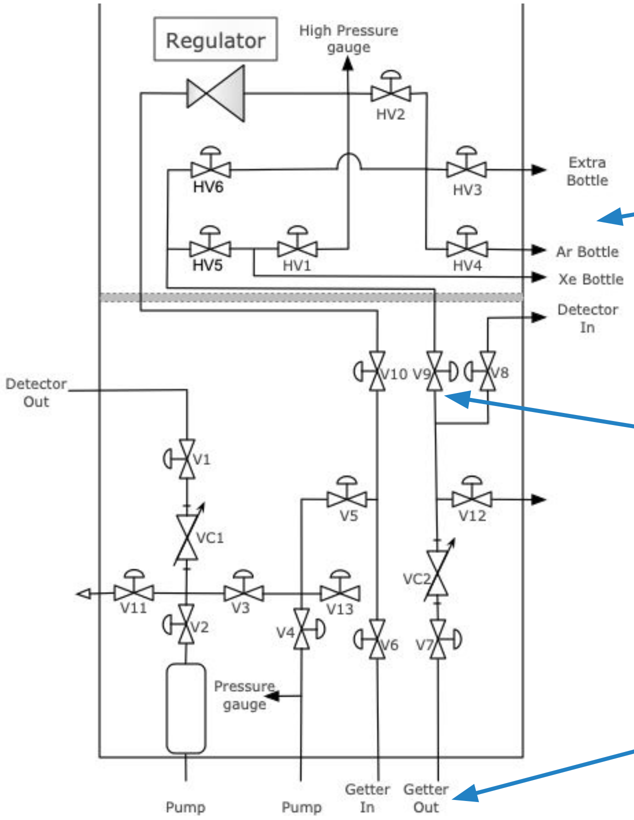
Ar gas liquefied through an **Heat Exchanger**, to fill cryostat with LAr



operation temperature is maintained by a **pulse tube refrigerator (PTR) cold head**

LN_2 circuit to improve cooling performance and to provide an emergency cooling system

Experimental setup: gas handling



controlled injection of Ar, Xe and contaminant, quantity regulated by **flow controllers**

bypass provides **direct injection of contaminants**

getter-based purifier for ultra-high purity at level of ppb of H_2, O_2, N_2, H_2O, CO_2

Experimental setup: light detection

VUV scintillation light read out directly by SiPMs

- first choice **VUV-HD Cryo technology** developed by **Fondazione Bruno Kessler** (NIMA 982 (2020) 164478)
  - **high detection efficiency**, **anti-reflective coating** and **low afterpulsing**
  - **FBK available for research run** to improve VUV SiPMs and find an optimal configuration
- **backup solution** with commercial available VUV SiPM (e.g., VUV4-MPPC from Hamamatsu)
- **standard SiPM** coated with wavelength shifter (TPB) as reference configuration

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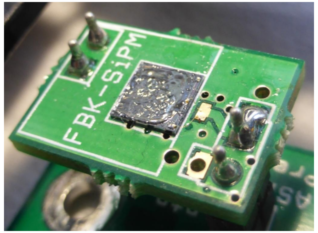
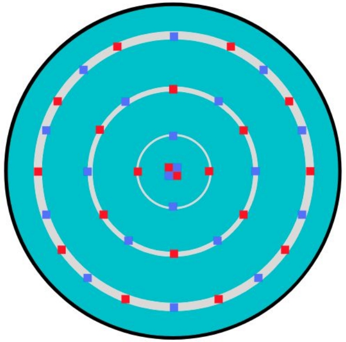
BRUNO KESSLER



SiPM array with 25 VUV-sensitive + 25 standard



Impact

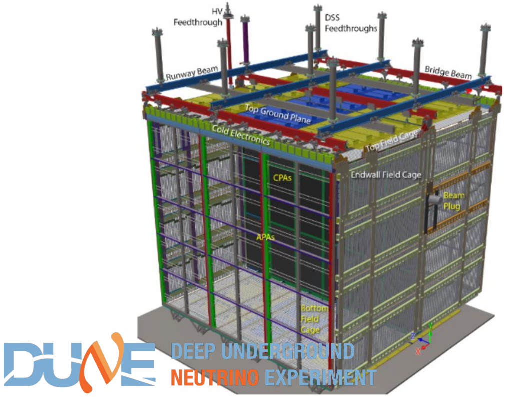
Direct impact in experiments based on LAr: LEGEND, DUNE, DarkSide, DEAP

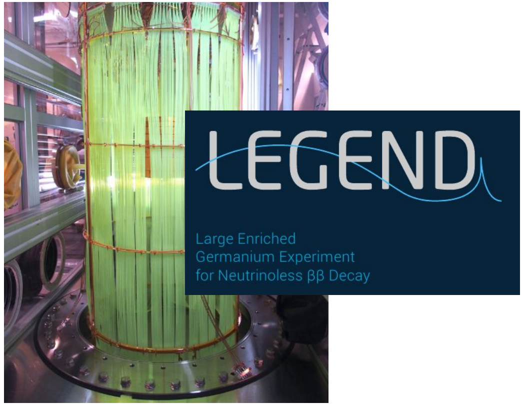
At the moment the Xe-doped LAr is being considered by:

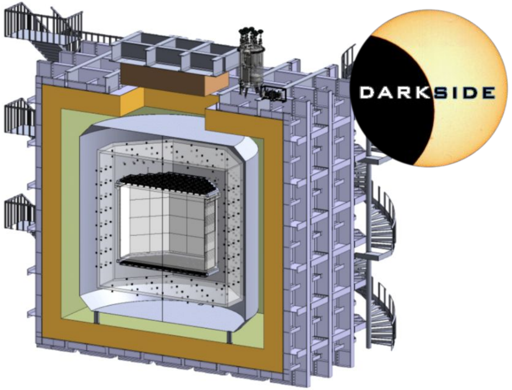
DUNE to increase the uniformity of light propagation (reducing impurity suppression)

LEGEND-1000 to improve light detection of LAr veto and reduce background

DarkSide-20k with the idea to search for neutrinoless $\beta\beta$ decay with isotope ^{136}Xe







Other applications based on Xe-doped LAr include:

- medical physics, to build a **3D time-of-flight PET scanner** (LAr TOF-PET Workshop ‘18)
- **large size inspection systems** for air and maritime containers (2012 JINST **7** C03007)

Organization

Research Units

Name	Institute	FTE
Valerio D'Andrea	INFN Laboratori Nazionali del Gran Sasso	0.8
Natalia Di Marco	(& GSGC Connected Group)	0.1
Alfredo D. Ferella		0.1
Matthias Laubenstein		0.1
Carla Macolino		0.2
Michele Morella		0.3
Giuseppe Salamanna	University of Roma Tre	0.25
Carla Cattadori	INFN Milano Bicocca	0.2
Total		2.05

Synergies with external projects

- collaboration with research groups from **LEGEND**, **DUNE** and **DarkSide** (INFN CSN2)
- **FBK** is showing interest in the improvement of VUV-sensitive SiPMs

Costs

First year	Estimated Cost
Cryostat	20.000 €
Cold head	25.000 €
Gas handling and purification system	25.000 €
Consumables (connectors, cables, cleaning products)	2.000 €
n. 1 GAr bottle pack (16 x 50 l)	1.500 €
Services	1.500 €
Total	**75.000 €**

Cryostat is the high priority in the first phase, choose carefully design and ask different companies

PTR Cold Head and **Getter** are the crucial components of cryogenics and gas systems

FBK is available to perform a research run for VUV-SiPM (we evaluate this opportunity)

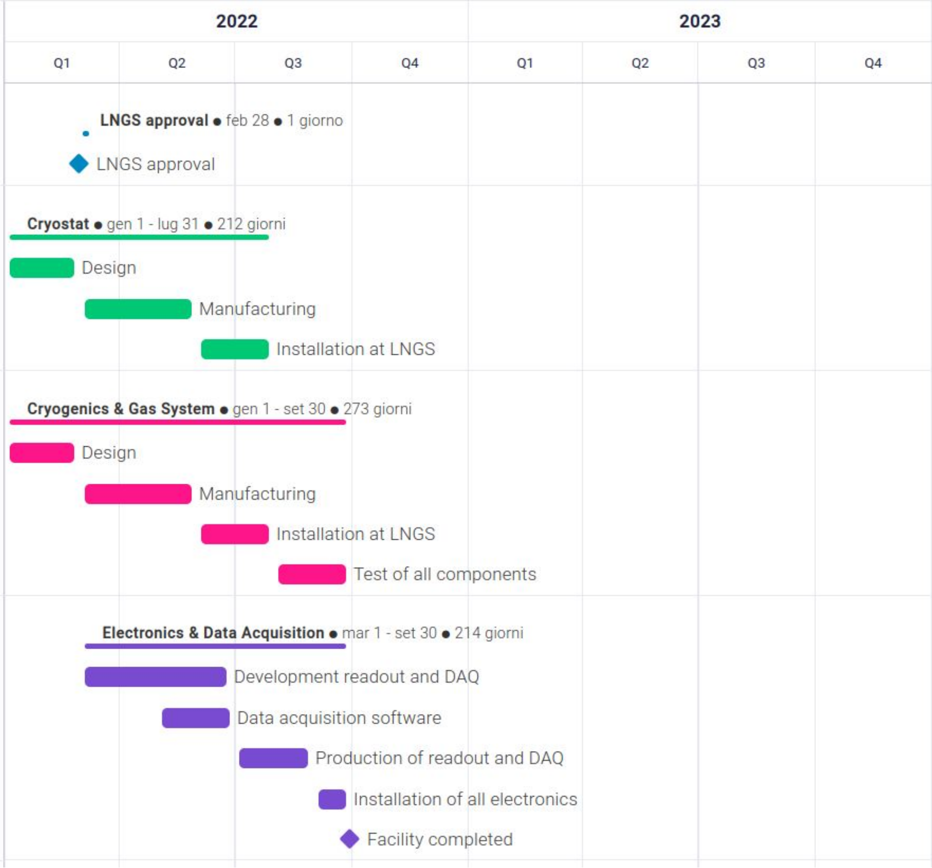
High-purity Ar splitted in two years (cryostat cooling and first filling and long term operation)

High-purity Xe cost is variable, Air Liquide estimated for ~1 kg

Second year	Estimated Cost
VUV-sensitive SiPMs (research run)	25.000 €
VUV-sensitive SiPMs (production)	10.000 €
Readout electronics and DAQ for SiPMs	10.000 €
n. 3 GAr bottle pack (16 x 50 l)	4.500 €
High-purity Xe bottle (2 l)	3.500 €
Calibration sources	1.500 €
Standard SiPMs	1.000 €
Consumables (connectors, cables, cleaning products)	3.000 €
Services	2.000 €
Travels to manufacturers	5.000 €
Total	**65.500 €**

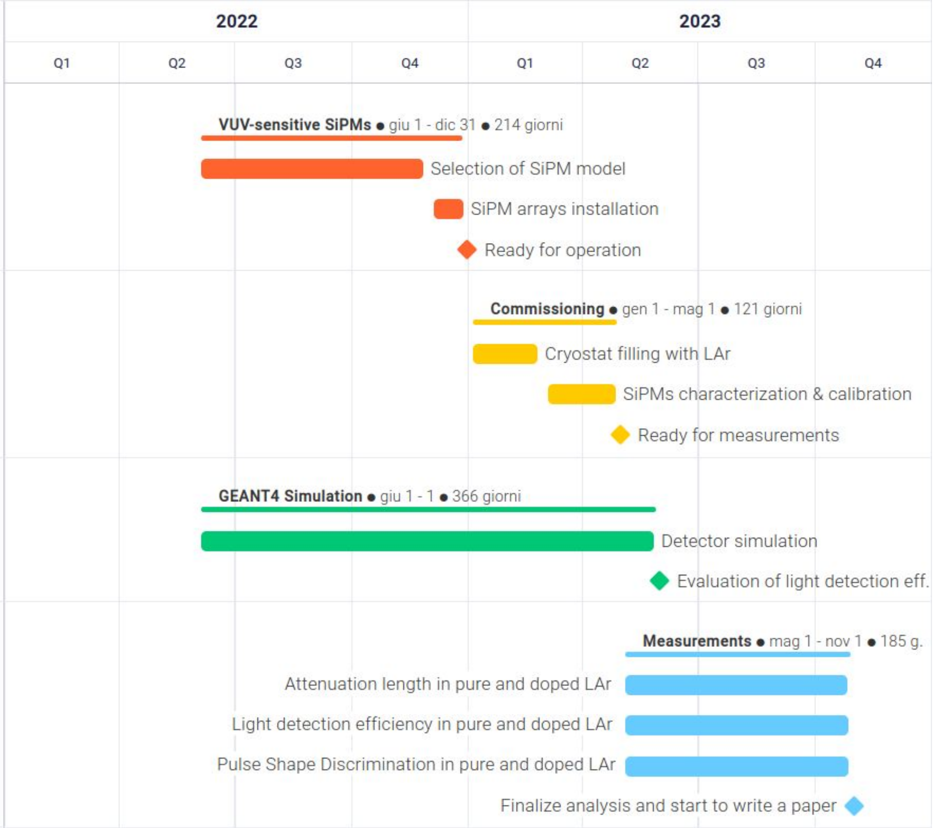
Time schedule

LNGS approval	
LNGS approval	feb 28
Cryostat	
Design	gen 1 - feb 28
Manufacturing	mar 1 - mag 31
Installation at LNGS	giu 1 - lug 31
Cryogenics & Gas System	
Design	gen 1 - feb 28
Manufacturing	mar 1 - mag 31
Installation at LNGS	giu 1 - lug 31
Test of all components	ago 1 - set 30
Electronics & Data Acquisition	
Development readout and DAQ	mar 1 - giu 28
Data acquisition software	mag 1 - giu 30
Production of readout and DAQ	lug 1 - ago 31
Installation of all electronics	set 1 - 30
Facility completed	set 30



Time schedule

Task	Dates
VUV-sensitive SiPMs	
Selection of SiPM model	giu 1 - nov 30
SiPM arrays installation	dic 1 - 31
Ready for operation	dic 31
Commissioning	
Cryostat filling with LAr	gen 1 - feb 28
SiPMs characterization & calibration	mar 1 - apr 30
Ready for measurements	mag 1
GEANT4 Simulation	
Detector simulation	giu 1 - mag 31
Evaluation of light detection efficiency	giu 1
Measurements	
Attenuation length in pure and doped L...	mag 1 - ott 30
Light detection efficiency in pure and d...	mag 1 - ott 31
Pulse Shape Discrimination in pure and...	mag 1 - ott 31
Finalize analysis and start to write a pa...	nov 1



Summary

- **liquid argon (LAr)**, leading technology in fundamental physics, presents **non-optimal features** such us VUV light emission, decay time ~μs and short attenuation length
- **doping with a little amount of Xe** seems to improves LAr properties, the situation is not completely clear and divergent results are available on:

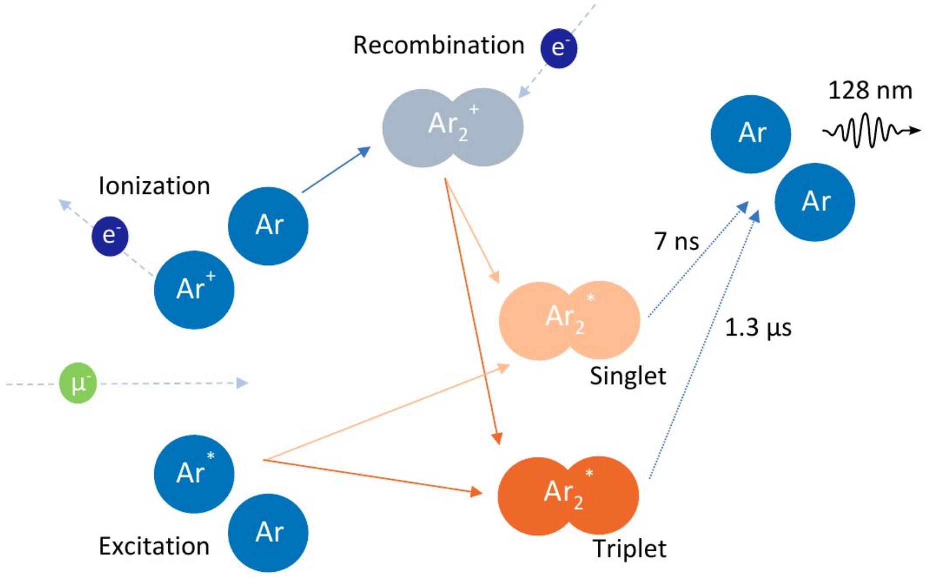
    a. **LAr attenuation length**
    b. **light detection efficiency**
    c. **signal shape and discrimination**
    d. **LAr light yield**

- **AL&X** aims to clarify such aspects with an innovative setup including **extremely high-purity criteria** and read LAr scintillation light with **VUV sensitive SiPMs**
- the final goal is to test **Xe-doped LAr** solution as alternative to:

    a. **pure LAr detectors**, improving light properties
    b. **LXe detectors**, avoiding high Xe cost (~3000 €/kg)

Backup

LAr scintillation



Ionizing particles release energy in LAr that can be **excited Ar*** or **ionized Ar^+**

- **excitons** form Ar_2^* interacting with Ar
- **ions** form Ar_2^+ that recombines with e^- producing an Ar_2^* excimer

excited Ar_2^* molecule can be formed in two states, singlet and triplet that decay radiatively emitting 128 nm photons

Direct excitation produces more singlet states than recombination process. Since atomic excitation is more probable in **nuclear recoil** interactions (w.r.t. **electronic recoil**), singlet states have a greater component in nuclear recoil interactions

Light detection efficiency

$$\varepsilon = e^{-l/\lambda_{LAr}} \cdot \mathrm{WLSE} \cdot \mathrm{PDE} \cdot \varepsilon_{geom}$$

- λ_{LAr} = LAr attenuation length
- WLSE = wavelength shifter efficiency, ratio between number of re-emitted photons and incident photons
- PDE = photon detection efficiency of light sensor
- ε_{geom} = geometrical efficiency

High-purity Cryostat

Alca Technology and **Saes Rial Vacuum** produce cryostats suitable to operate high-purity LAr:

- double wall chamber in AISI 304L electropolished and tested in ultra high vacuum
- (Tungsten Inert Gas) TIG welding certified to work at cryogenic temperature

Other specialized companies like **Criotec Impianti** will be also considered, since can have suitable commercial products

PT30 Cold Head by Criomech

CRYOMECH

The **pulse tube refrigerator (PTR)** is a cryocooler made without moving parts in the low temperature part, making it suitable for a wide variety of applications including research

PT30 Cryorefrigerator w/ 4 Channel Temperature Measurement and Control

	Description	Part Number	List Price
1	PT30 Cold Head	CH3C030	$13,475.00
1	Helium Compressor Package		
	CP820, Water Cooled, 200VAC; 1 Ph; 50 Hz	CP0802W2HF	
1	Step Down Transformer	ETR106	
	(Necessary if 50 Hertz voltage supply is greater than 220VAC.)		$660.00
	Stainless Steel Flexible Lines		
1	1/2" ID, Standard, 1/2" Aeroquip both ends, 10 Ft. Long	FL08S-0808-10	
1	1/2" ID, Standard, 1/2" Aeroquip both ends, 10 Ft. Long	FL08S-0808-10	
1	Cold Head Motor Cord, 10 Ft. Long	MC-6808-10	
1	Installation and Operation Manual	IMC018	
1	Installation Tool Kit	ITK002	
	Temperature Measurement and Control		
1	Electrical Feedthrough Single Stage	TBD	$600.00
1	CTC 4 Channel Temperature Controller (CPN: TRE588)	TBD	$4,550.00
4	Lakeshore Diode (CPN: DT-670A-CU)	TBD	$5,220.00
1	Watlow Fire Rod Cartridge 50V 100W Heater	TBD	$115.00

PS4 Monotorr Heated Getter by SAES

In order to improve and maintain the vacuum environment inside hermetically sealed devices, the getters materials can sorb all active gases such as O_2, H_2O, CO, CO_2 and N_2 by a chemical reaction under vacuum

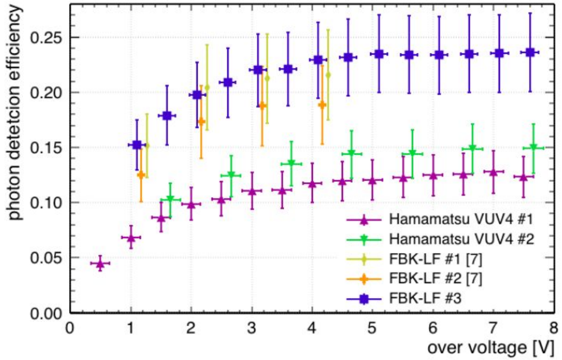
The **Heated Getter technology** forms an irreversible bond with the impurities and removes them to sub-ppb levels. Unlike ambient purification technologies that rely on surface sorption only, heated getter technology utilizes the **entire volume** of material resulting in superior impurity capacity and longer purifier lifetime

VUV sensitive SiPM

Research group and companies are putting effort in the developments of SiPMs that promise higher PDE, higher reliability at LAr temperature and much higher radiopurity than PMTs

FONDAZIONE BRUNO KESSLER

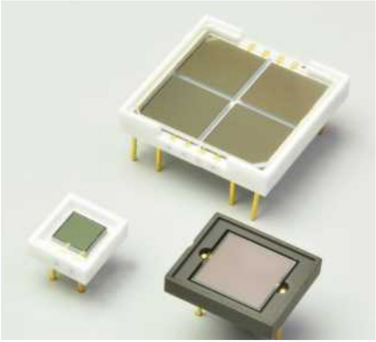
FBK optimized VUV light detection and cryogenic temperature operation in the **VUV-HD-Cryo technology**

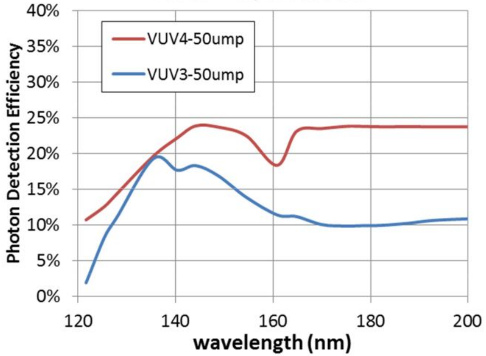


HAMAMATSU

PHOTON IS OUR BUSINESS

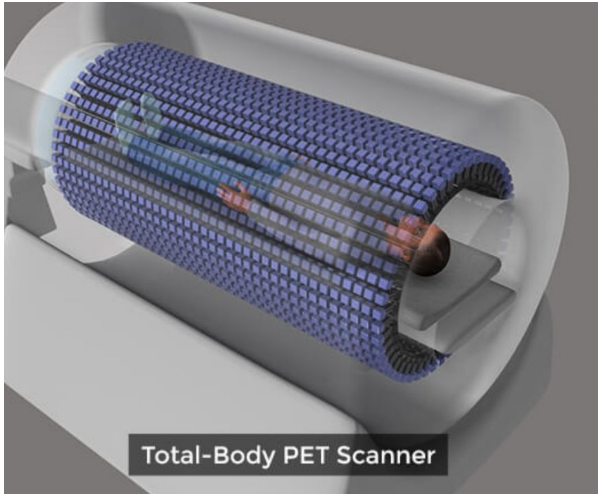
VUV Multi-Pixel Photon Counter (MPPC) 4th generation by **Hamamatsu Photonics**

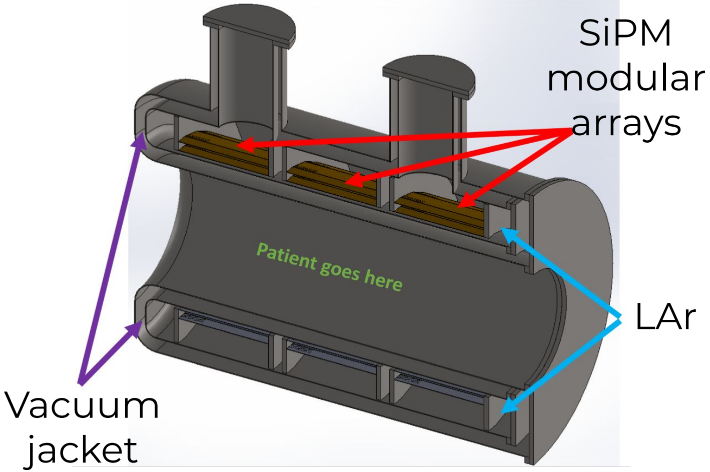




Total-Body TOF-PET with LAr

Total-Body Time of Flight (TOF) PET is a promising technology with true 3D reconstruction, scan entire body at once, increases sensitivity for gamma detection



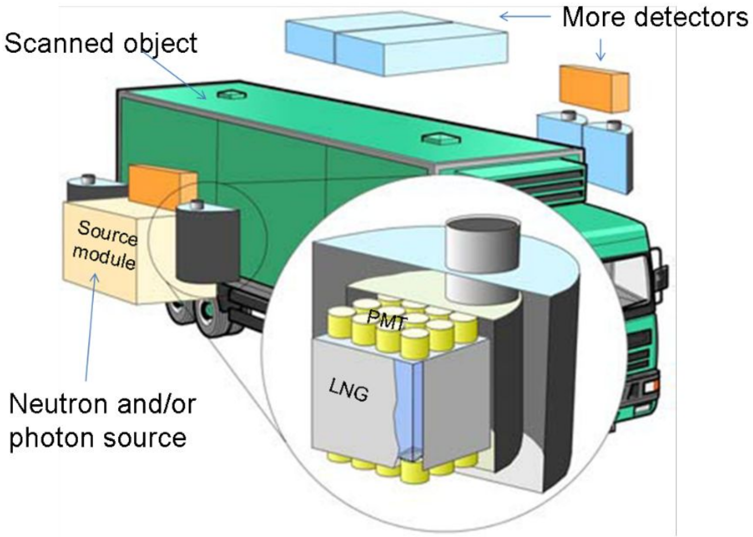


LAr is considered as alternative to LYSO scintillator for higher LY, longer attenuation length, cost effective. Xe-doping can improve time resolution (avoid TPB and suppress triplet component), needs to be further studied to understand light time profile and spectrum

LAr TOF-PET Workshop ‘18

Non-Intrusive Inspection for Containers

Research groups are investigating the suitability of LAr as a scintillation material for **large size inspection systems** for air and maritime containers and trucks



The system detects fission gamma rays and fast neutrons emitted spontaneously or by stimulation from nuclear materials

In the context of **Special Nuclear Material** detection systems is investigated the possibility to use LAr and LAr doped with Xe, to obtain faster response and higher energy resolution

2012 JINST **7** C03007